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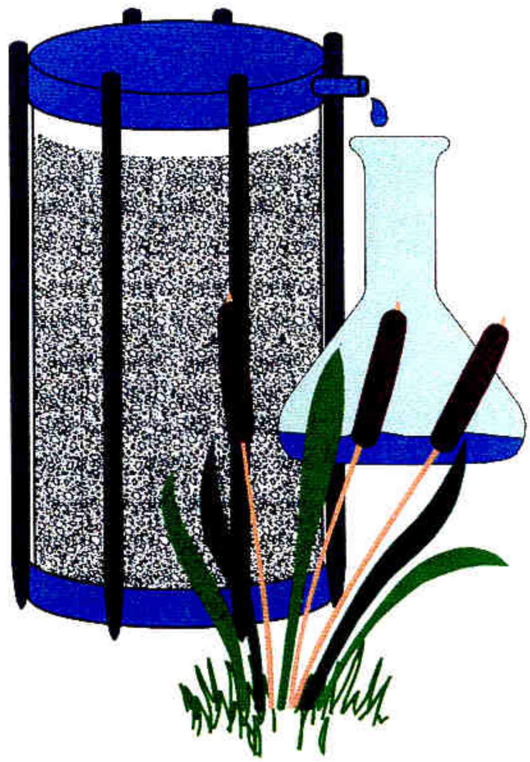
Disposal Cell Cover Moisture Content and Hydraulic Conductivity

Long-Term Surveillance and Maintenance Program Shiprock, New Mexico, Site

May 2001



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Long-Term Surveillance and Maintenance Program
Shiprock, New Mexico, Site

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Acronyms

AEP	air-entry permeameter
ANOVA	analysis of variance
cm	centimeters
cm^3	cubic centimeters
cm/d	centimeters per day
cm/s	centimeters per second
CPN	Campbell Pacific Nuclear
CSL	compacted soil layer
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
g/cm^3	grams per cubic centimeter
GJO	Grand Junction Office
hr	hours
in	inches
kg	kilograms
K_{sat}	saturated hydraulic conductivity
LTSM	Long-Term Surveillance and Maintenance
m	meter
pCi/l	picocuries per liter
NRC	U.S. Nuclear Regulatory Commission
RRM	residual radioactive material
SEM	standard error of the mean
UMTRA	Uranium Mill Tailings Remedial Action
UMTRCA	Uranium Mill Tailings Radiation Control Act

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Executive Summary

The Shiprock, New Mexico, Uranium Mill Tailings Remedial Action (UMTRA) disposal cell was constructed by the U.S Department of Energy (DOE) to isolate uranium mill tailings and contaminated soil in order to minimize radon emanation and moisture infiltration. The purpose of this study, conducted by the Environmental Sciences Laboratory for the DOE Long-Term Surveillance and Maintenance (LTSM) Program, was to evaluate evidence of water movement through the Shiprock UMTRA disposal cell cover as requested by the Navajo Nation. Percolation of precipitation through the cover and tailings is a potential source of ground water contamination. This report presents methods and results of physical property tests of cover materials, hydroprobe monitoring of soil moisture profiles in the cover from June 1999 through September 2000, and in situ measurements of the saturated hydraulic conductivity. A barrel calibration method was used to calculate volumetric moisture content as a function of neutron counts.

A summary of the conclusions and recommendations follows:

- The compacted soil layer (CSL or radon barrier) consists of highly compacted silt loam soil.
- Voids in a surface rock layer have half filled with windblown silt and fine sand since construction of the disposal cell in 1986.
- The CSL in the cover was essentially saturated in 2000.
- CSL moisture content measurements show minimal variation from one location to another, with depth or over time.
- Hydroprobe monitoring indicates that the top of the tailings was also essentially saturated in 2000. The saturation of the tailings was confirmed. The neutron hydroprobe was consistently dripping wet when extracted from probe ports into the tailings, even after the ports had been bailed.
- The in situ saturated hydraulic conductivity of the CSL, measured on the north side slope as part of a 1998 root intrusion study, was highly variable and significantly greater than the design target of 1.0 H 10^{-7} cm/s.
- A 1988 laboratory measurement of the saturated hydraulic conductivity (K_{sat}) of the tailings suggests that the upper tailings layer may have a much lower K_{sat} than the CSL, possibly causing water percolating through the cover to perch on the tailings. This may be the reason for standing water in the bottom of the hydroprobe ports.
- Given apparently high variability in the K_{sat} of the CSL and apparently low K_{sat} of the tailings, conclusions of this study are the basis for a recommendation to DOE to conduct representative tests of the physical and hydraulic properties of the CSL <u>and</u> tailings layer to evaluate water flux through the disposal cell.

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1.0 Introduction

The U.S. Department of Energy Grand Junction Office (DOE–GJO) Long-Term Surveillance and Maintenance (LTSM) Program provides stewardship services for DOE sites across the country containing low-level radioactive materials (*www.gjo.doe.gov/programs/ltsm/*). Included in the LTSM Program are uranium mill tailings disposal cells constructed under the auspices of the Uranium Mill Tailings Radiation Control Act (UMTRCA) to contain contaminants for 1,000 years. In 1998, the LTSM Program initiated the Cover Monitoring and Long-Term Performance Project to evaluate how changes in UMTRCA disposal cell environments, both observed changes and changes projected over hundreds of years, may alter the performance of disposal cells (DOE 2001). The LTSM Program and the DOE Environmental Sciences Laboratory are evaluating the hydrologic performance of the Shiprock, New Mexico, uranium mill tailings disposal cell in response to a request by the Navajo Nation. This report presents the results of recent soil moisture and soil hydraulic property sampling in the disposal cell cover for comparison with sampling data from the late 1980s.

Five neutron hydroprobe access tubes were installed in the cover of the Shiprock disposal cell in 1988, penetrating approximately 325 centimeters (cm) through the rock layer, sand layer, and compacted soil layer (CSL) or radon barrier, and into the upper part of the interred tailings (Figure 1). We used four of these probe ports (the fifth port was blocked) to monitor moisture levels in the rock layer and CSL from June 1999 through November 2000. We also conducted a calibration study to relate neutron counts per minute, measured in the disposal cell cover profile using a neutron hydroprobe, to volumetric water content. Results of this recent monitoring period were compared with data on physical and hydraulic properties of the CSL acquired (1) in 1988 shortly after the disposal cell cover was constructed and (2) during a root intrusion study conducted in 1998.

The objectives of the current hydroprobe monitoring study at Shiprock were

- to evaluate moisture contents in the cover and tailings,
- to report any changes in the physical or hydraulic properties of cover materials, and
- to evaluate evidence for infiltration of a significant volume of water through the disposal cell cover and tailings.

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2.0 Background Information

The Shiprock, New Mexico, disposal cell was constructed in 1986 before the U.S. Environmental Protection Agency (EPA) proposed ground water quality standards for uranium mill tailings sites. The disposal cell cover was designed to address performance standards concerned with radon flux and longevity. The design standard for radon (40 CFR 192.02[b]) states that the remedial action should provide reasonable assurance that releases of radon-222 to the atmosphere will not (1) exceed an average surface flux rate of 20 pCi/m^{-2}/s^{-1}, or (2) increase the annual aver concentration of radon-222 in the air at or above any location outside the disposal site by more than 1/2 pCi/l^{-1}. EPA established a design life standard of 1,000 years whenever reasonably achievable (EPA 1983). In any case, a minimum performance period of 200 years must be achieved.

No ground water quality standards existed at the time the Shiprock disposal cell was constructed in 1986. In 1995 EPA published 60 FR 2854, the Final Rule for the control of residual radioactive materials (RRM) from inactive uranium processing sites. The Final Rule requires that remedial action be conducted to assure that amounts of RRM and associated hazardous constituents in ground water meet certain concentration standards. At sites like Shiprock where tailings were stabilized in place, compliance with groundwater standards may depend on an engineered cover that limits infiltration of meteoric water into buried RRM (DOE 1989). This may be achieved by maintaining unsaturated conditions in the cover, by including a highly permeable bedding or drainage layer in the cover, and/or by including a compacted, low-permeability soil layer in the cover. In 1988, DOE began an evaluation of the hydrological performance of the existing disposal cell cover at Shiprock (DOE 1989, 1991).

2.1 Shiprock Cover

The cover design used at Shiprock consists of three layers: a CSL or radon barrier to control radon releases and water infiltration, a sand or drainage/bedding layer overlying the CSL, and rock armor as the top layer. As with Resource Conservation and Recovery Act covers, the target saturated hydraulic conductivity for the CSL is 1 H 10^{-7}cm/s (Caldwell 1992). A CSL thickness adequate to meet the radon flux standard was calculated using an early version of the U.S. Nuclear Regulatory Commission (NRC) RADON model (NRC 1989). A sand drainage or filter layer also serves as a bedding layer for the rock armor. The rock armor is sized to prevent erosion of underlying layers given a probable maximum precipitation event, the most severe combination of meteorological and hydrological conditions possible at a site. The Shiprock top slope cover design consists of a 198-cm CSL overlying the tailings, a 15-cm sand drainage/bedding layer overlying the CSL, and a 30-cm cobble riprap layer overlying the bedding layer. The CSL is 214-cm thick on the side slopes of the disposal cell.

2.2 Neutron Hydroprobe Operation

Neutron hydroprobes, or neutron thermalization gauges, consist of a probe containing a source of high-energy neutrons and a detector for slow neutrons; a cable to lower the probe down access tubes; a probe housing with lead and polyethylene shields to absorb gamma rays and neutrons, respectively; and a scaler to display slow neutron counts. High-energy neutrons released from an americium-beryllium source in the probe are scattered and slowed (thermalized) by elastic collisions with hydrogen nuclei in the soil water. The slow neutrons interact with gases in the probe detector, releasing an alpha particle that causes an electric pulse recorded as a count in the scaling unit (Gardner 1986). The volume of soil measured by the probe varies depending on the concentration of hydrogen nuclei and, thus, primarily on soil water content. Since the development of neutron thermalization methods for measuring soil moisture (Gardner and Kirkham 1952: Van Bavel et al., 1956), advances in electronics and the use of less radioactive sources have improved efficiency, portability, safety, and precision. The standard error of estimated volumetric soil water content is often less than 0.01 cm^3 water per cm^3 dry soil (Gardner 1986). Details concerning the theory and operation of neutron thermalization gauges can be found elsewhere (Greacen 1981; Gardner 1986).

3.0 Methods

3.1 CSL Physical Properties

Soil bulk density, soil texture, soil water content, and porosity of the CSL and of soils in the borrow area used to construct the CSL were determined in the field. Adequate field sampling of these soil properties was necessary to design physical models for the hydroprobe calibration.

Three soil pits were excavated in the Shiprock cover adjacent to hydroprobe ports 205, 206a and 206b, and 208 on July 25, 2000 (Figure 1). Excavated rock and sand drainage-layer materials from the pit were separated on a tarp. The upper 10 to 15-cm excavated portion of the CSL was removed and piled separate from the rock and sand. Volume samples for bulk density analyses were retrieved with a double cylinder, hammer-driven core sampler. A hand-driven bucket auger was used to obtain bulk samples for analyses of soil texture and water content. Bulk samples of windblown soil deposited in the rock cover were also collected for textural analysis. Bulk soil samples were collected from eight random locations in the CSL borrow pit area for analysis of particle size distribution. Table 1 lists the laboratory methods used for analyses of gravimetric water content, dry-weight bulk density, soil porosity, and particle size distribution (texture). After the samples were collected, rock, gravel, and CSL materials were placed back in the pit in a layer sequence that closely matched the predisturbed condition.

3.2 Hydroprobe Calibration

A combination of an in situ field method and a barrel calibration method was used to determine volumetric soil moisture content as a function of neutron counts per minute measured by a Campbell Pacific Nuclear (CPN) neutron hydroprobe supplied by the Environmental Research Laboratory (Campbell Pacific Nuclear 503 DR, Serial No. 1475). Neutron counts (counts per minute) were recorded in hydroprobe ports 205, 206a, 206b, and 208 just before the pits were excavated to sample soil physical properties. Simultaneous readings of soil density using a CPN density-moisture meter were attempted, but the aluminum probe ports were not wide enough for the probe to pass freely into the tube. Micrometer measurements showed that the exposed portions of the probe ports were slightly out of round, varying from 4.75 –5.41 cm, while the probe diameter was 4.83 cm.

A barrel calibration was performed using the borrow area soil to simulate the CSL. The soil was air dried and then placed in a 210-l (50-cm-diameter) barrel. An aluminum neutron hydroprobe port of the same wall thickness (0.124 cm) and internal diameter (5.08 cm) as the Shiprock ports was installed in the center of the barrel. Soil was placed in the barrel and compacted in an attempt to achieve the same bulk density as measured in the Shiprock cover CSL. Exactly 198.85 kg of dry soil was layered into the barrel in 10-cm lifts and compacted with a metal tamper. The bulk density of the soil (ρ_b, grams of soil per cubic centimeter of soil) in the barrel was determined by calculating the depth of soil (*d* in centimeter) in the barrel (measured at 10 or more points on the soil surface), the oven-dry weight of soil placed in the barrel (m_s in grams), and the cross sectional area (*a*, in square centimeters) of the barrel:

$$\rho_b = m_s/(d)(a) \qquad (1)$$

The barrel was filled to within about 40 cm of the top with compacted soil. A bulk density of 1.90 grams per cubic centimeter (g/cm^3) was measured for the dry soil. The neutron count (counts per minute) of the dry soil was measured with the neutron hydroprobe lowered down the aluminum port to the center of the barrel. Sufficient water to bring the moisture content to 0.15 cm^3/cm^3 was added to the top of the soil. After allowing this water to infiltrate for 48 hours (hr), the soil was compacted further by tamping. The addition of moisture allowed the soil to be compacted to a final dry-weight bulk density of 1.98 g/cm^3.

When a neutron hydroprobe measurement of 0.15 cm^3/cm^3 moisture was achieved, 15 cm of additional water was added to the top of the soil and allowed to infiltrate. Neutron counts in the barrel were recorded periodically over 290 hr as the water infiltrated the soil. A control barrel filled with water was used to account for evaporation rate (ca. 0.2 cm/day). After approximately 100 hr, water began to drain from the bottom of the calibration barrel, indicating that the soil was saturated. At 290 hr, the initial volume of water added to the barrel had completely infiltrated into the soil or evaporated. An additional 5 cm of water was added to the surface and allowed to infiltrate and drain to ensure even wetting. When no further water drained from the barrel for 24 hr, considered to be the field capacity of the soil, the neutron hydroprobe was lowered to the center of the barrel to record neutron counts. Three 60-g soil samples were taken from the barrel for a gravimetric determination of water content. Results were recorded as volumetric or volumebasis water content (θ_{vb}, cubic centimeters of water per cubic centimeter of soil) using the equation (Gardner 1986)

$$\theta_{vb} = (\rho_b/\rho_w)\theta_{dw} \qquad (2)$$

where

ρ_b = dry-weight bulk density of the soil (g soil/cm^3 soil),
ρ_w = density of water (1.0 g water/cm^3 water), and
θ_{dw} = dry-weight or gravimetric soil moisture content (g water/g dry soil).

3.3 Hydroprobe Monitoring in Cover

Neutron counts (counts/minute) were monitored monthly in hydroprobe access ports 205, 206a, 206b, and 208 in the Shiprock cover from June 1999 through September 2000 (Figure 1). Use of the neutron hydroprobe followed the procedures of Gardner (1986). Figure 2 shows the depth of neutron probe ports relative to cover and tailings layers. Port 207 was blocked with debris at a depth of about 80 cm and was not monitored regularly. Port 206b was blocked initially, but the obstruction was removed in September 1999. Counts were recorded at 15.24-cm (6-in.) increments from the top of the hydroprobe access ports to a depth of 351 cm (138 in.). The 15-cm counts were above the ground surface, the 30-cm counts were near the top of the rock layer, the 46-cm counts were near the bottom of the rock layer, and the 61-cm counts were in the sand drainage layer. Data for 76-cm to 259-cm depths were from the CSL and counts at 274 cm and below were in the tailings.

3.4 In Situ Hydraulic Conductivity

In 1998, DOE evaluated the effects of root intrusion on the saturated hydraulic conductivity (K_{sat}) of the CSL. Air-entry permeameters (AEPs) were used to estimate in situ K_{sat} in areas on the north side slope of the disposal cell cover where several typically deep-rooted plant species were growing (Figure 1). The AEPs were designed and manufactured by Daniel B. Stephens and Associates, Inc. (Stephens et al. 1988; Havlena and Stephens 1992). The AEP, based on a design by Bouwer (1966), consists of a round, 30-cm-deep permeameter ring, air-tight cover, standpipe, graduated water reservoir, and vacuum gauge.

Three pits were excavated where three different species were rooted into the CSL (Figure 1): tamarisk (*Tamarix ramosissima* Ledeb.), rubber rabbitbrush (*Chrysothamnus nauseosus* [Pall. ex Pursh] Britton), and Russian thistle (*Salsola kali* L.). AEP measurements were made within each pit where roots penetrate the CSL and in an adjacent location where plant root intrusion was not observed. After installing the permeameter ring, we sealed polycarbonate plates to the top of the ring, attached standpipes and water reservoirs, and filled the reservoirs. Reservoir water was dyed to trace wetting fronts and preferred flow paths. The two-stage test consisted of (1) measuring the rate of water-level drop in the reservoir and (2) measuring the pressure (tension) with the vacuum gauge after shutting off the water supply and allowing time for water to redistribute. The vacuum gauge measurement was used to calculate the air-entry or bubbling pressure of the soil (ASTM D5126–90). Within each of the three test pits, core samples of the CSL were taken to determine soil moisture content, bulk density, and porosity using the methods described in Section 3.1.

Using the AEP method (Bouwer 1966; Havlena and Stephens 1992), saturated conductivity (K_{sat} in cm/s) was calculated as

$$K_{sat} = [2 * dH/dT * L * (R_{ws}/R_{sr}) * 2]/[H_f + L - (0.5 * P_a)] \qquad (3)$$

where

dH = change in head,
dT = change in time,
L = depth of soil surface to wetting front,
R_{ws} = radius of water supply reservoir,
R_{sr} = radius of AEP soil ring,
H_f = last head reading,
P_a = $P_{min} + G + L$,
P_{min} = gauge pressure at air entry (negative value), and
G = height of gauge above the soil surface

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4.0 Results and Discussion

4.1 Physical Properties of CSL and Borrow Soils

The cover CSL and most of the borrow area soils are classified as silt loam. However, the borrow area samples tend to have higher sand splits and lower clay splits than the cover CSL. On the basis of this comparison, we selected sample location SBA–7 in the soil borrow area to build the hydroprobe calibration barrel. Sand-silt-clay splits at sample location SBA–7 are 23-58-19 compared to an average of 19-58-22 in the cover CSL. Table 2 presents soil particle-size distribution and texture results for the Shiprock cover CSL and borrow area soils.

Table 3 shows gravimetric moisture content of drainage layer sand, gravimetric moisture content of the CSL, dry-weight soil bulk density and calculated porosity of the cover CSL, and the calculated percent saturation of the CSL. Cover CSL samples were removed from a depth of approximately 30 cm below the sand-CSL contact. The mean bulk density of the CSL (1.98 g/cm^3) was used as the target for soil compaction in the calibration barrel.

Percent saturation (mean = 97.1, Standard error of the mean [SEM] = 5.16) was calculated using bulk density of the CSL (mean = 1.93 g/cm^3, SEM = 0.012 g/cm^3, n = 71) and the mean particle density of the CSL (mean = 2.72, SEM = 0.003, n = 93) from the 1988 study. The 1988 bulk density values were less than those measured in the current study (mean = 1.98 g/cm^3, SEM = 0.04 g/cm^3, n = 3). Using the 1988 mean bulk and particle density values, the equivalent mean porosity is 29.04 percent.

Table 4 presents soil particle-size distribution for fines sampled from the rock layer in the three pits. These materials filled approximately half of the interstitial voids in the rock layer and are assumed to be windblown soil from surrounding areas. If, indeed, most or all of the fines in the rock layer are windblown, then complete filling of the interstitial voids during the first decades of the 21st century is a reasonable projection. Two consequences are likely: establishment of a contiguous plant cover and greater water retention above the CSL.

4.2 Hydroprobe Calibration

Soil moisture content of samples taken from the calibration barrel was correlated with counts-per-minute data recorded with the neutron hydroprobe in the barrel. A strong linear relation was identified between volumetric soil moisture and counts recorded with the hydroprobe (Figure 3). The equation of best fit had a high coefficient of determination (r^2 = 0.99); neutron hydroprobe and soil moisture data from the cover clustered at the wet end and were omitted from the calibration. This equation was used to convert monthly count data at different soil depths to estimates of volumetric soil moisture content. The moisture content of the three samples taken from the calibration barrel at field capacity was 0.301 cm^3/cm^3 (SEM = 0.006, n = 3). Given a dry-weight bulk density range of 1.90 to 1.98 g/cm^3 from Equation (1) and a measured particle density range of 2.66 to 2.78 g/cm^3 from the 1988 data, then the equivalent range of porosity values is 0.26 to 0.32. Therefore, we assume that for the wet point measurements in the calibration barrel, soil samples were 94-percent saturated, at a minimum, and likely close to 100-percent saturated. The rate of water infiltration into this saturated or near saturated soil in the calibration barrel was 3.84 H 10^{-2} cm/hr or 1.07 H 10^{-5} cm/s as indicated by the slope in Figure 4.

4.3 Moisture Levels in Shiprock Cover

Figure 5 presents moisture content in the disposal cell by depth from the top to the bottom of the hydroprobe ports averaged for data from all probe ports and for all dates. The sand drainage layer ended and the CSL layer began between the 60 and 76 cm depths. Moisture content increased from the top of the hydroprobe ports in the rock layer, reaching 35-percent volume in the sand layer, then remained at approximately 28-percent volume to the bottom of the probe ports. Variability was much greater above the CSL in the sand and rock layers than within the CSL.

Data were analyzed utilizing Statistix 7, a package of statistical programs from Analytical Software (P.O. Box 12185, Tallahassee, FL, 32317–2185). Data from the sand and rock layers (less than 76 cm depth) and the CSL were analyzed separately. For each group, we conducted a one-way analysis of variance (ANOVA) for each of three factors: probe, date, and depth. The dependent variable was soil water content (cm^3/cm^3) in each case. Each result shown in Table 5 was a one-way ANOVA. The subscript numbers in the ANOVA *F* value column indicate the degrees of freedom among and within groups. The rock layer in Table 5 represents soil depths to 76 cm, and the CSL layer represents greater depths including the tailings. All the factors had statistically significant effects, with the exception of the probe factor for the rock layer samples. Although the differences among groups in the other analyses were statistically significant, the powers of the tests were high because of the larger sample size, and, in most cases, the differences were not relevant. However, it was evident, even without a confirmatory statistical test, that soil water content increases with depth from the rock layer to the sand layer.

4.4 CSL Saturated Hydraulic Conductivity

Results of the 1998 K_{sat} study contrast sharply with other physical and hydraulic property data from the site (Table 6). The in situ K_{sat} values for the CSL were highly variable, with a range of nearly 4 orders of magnitude and a high of 1.29×10^{-4} cm/s. In contrast, DOE (1989) reported a much lower laboratory K_{sat} for CSL (mean = 5.6×10^{-7} cm/s; range = 2.3×10^{-6} to 6.4×10^{-8} cm/s). Contrary to our expectations, CSL K_{sat} values were actually lower in locations where roots penetrated the CSL than in locations with no observed root intrusion.

4.5 Physical and Hydraulic Properties of Tailings

This section summarizes the tailings data acquired during the 1988 study (DOE 1989). Tailings samples were taken at various depths during installation of hydroprobe ports 203, 206a, 206b, 207, and 208 (Figure 1). Soil moisture content, bulk density, particle density, and saturated hydraulic conductivity were measured; the saturated conductivity was reported as 3.5×10^{-8} cm/s (Table 7).

5.0 Conclusions

DOE is developing ground water restoration plans for the former uranium-ore processing site at Shiprock. DOE recognizes that containment of sources of ground water contamination is an important element of a successful environmental restoration effort at Shiprock. Evaluations of possible rates of water movement through the disposal cell cover and tailings, potential seepage rates out the bottom of the disposal cell, and effects of seepage mixing in the saturated zone may be needed to assure that long-term ground water cleanup goals will be achieved. As part of DOE’s evaluation of the performance of the Shiprock disposal cell, this study compared recent soil moisture and hydraulic conductivity monitoring data of the disposal cell cover with monitoring data from a 1988 study.

5.1 Soil Physical Properties

The cover CSL consists of highly compacted silt loam soil. Soils sampled in the CSL borrow pit area were also a silt loam and, therefore, suitable for construction of a neutron hydroprobe calibration model for the CSL. Voids in the 30-cm-thick rock layer have half filled with windblown silt and fine sand since construction of the disposal cell in 1986. Over time this infilling will create a more favorable habitat for plant establishment.

5.2 Hydroprobe Calibration

The soil texture and bulk density of the hydroprobe calibration barrel almost matched the actual Shiprock CSL. Therefore, the linear calibration ($r^2 = 0.99$) produced volumetric soil moisture data with relatively low measurement error.

5.3 Cover and Tailings Moisture Content

The CSL in the Shiprock cover was essentially 100-percent saturation in 2000. Therefore, saturated flow is most likely occurring in the CSL. Although some seasonal wetting and drying of the sand drainage layer occurs, the sand layer remains relatively wet (mean = 35 percent by volume) all year.

The moisture content of the CSL changed little from one hydroprobe port location to another, with depth, or over time. The moisture content of the CSL (mean = 28.8 percent by volume, SEM = 0.6) and the porosity of the top of the CSL (27.1 percent, SEM = 1.7) are statistically the same; therefore, the CSL is essentially 100-percent saturated. The moisture content of the top of the tailings (mean = 27.9 percent by volume, SEM = 0.9) and the calculated porosity of the tailings from the 1988 data (29.4 percent, SEM = 2.4 percent) are also statistically the same. Thus, we can infer that the top of the tailings is also 100-percent saturated. The fact that the neutron hydroprobe comes up dripping wet when lowered into the tailings, even after the port has been bailed, confirms this.

5.4 Saturated Hydraulic Conductivity of CSL and Tailings

The in situ saturated hydraulic conductivity of the CSL, measured on the north side slope as part of a 1998 root intrusion study, was highly variable (range = 4.8×10^{-8} to 1.2×10^{-4} cm/s) and significantly greater (mean = 4.4×10^{-5} cm/s, SEM = 2.5×10^{-5}) than the design target of 1.0×10^{-7} cm/s. One 1988 laboratory measurement of the K_{sat} of the top layer of tailings (3.5×10^{-8} cm/sec) suggests that top layer may have a much lower K_{sat} than the CSL. If true, water percolating through the cover may perch on the tailings. This may be the reason for the standing water in the bottom of the hydroprobe ports.

5.5 Water Flux

If the CSL is continuously saturated, as neutron hydroprobe data indicate, then the passage of water through the CSL and tailings would be greatly influenced by the K_{sat} of both. Under saturated conditions, the hydraulic gradient is approximately 1 and water flux through the cover can be estimated with Darcy's law. Given apparently high variability in the K_{sat} of the CSL and apparently low K_{sat} of the tailings, it is recommended that DOE conduct representative tests of the physical and hydraulic properties of the CSL <u>and</u> tailings layer to evaluate water flux through the disposal cell.

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Table 1. Summary of Laboratory Methods for Soil Analyses

Soil Property and Method	Reference
Gravimetric Water Content	Klute (1986), Chapter 21, pp. 493-544
Dry-Weight Bulk Density	Klute (1986), Chapter 13, pp. 363-367
Soil Porosity	Klute (1986), Chapter 18, pp. 444-445
Particle Size Distribution	
Sieve	Klute (1986), Chapter 15, pp. 383-442
Hydrometer	Klute (1986), Chapter 15, pp. 383-442

Table 2. Soil Particle Size and Texture Classification for Shiprock Cover CSL and Borrow Area

Sample Location	Sample Number	Sand (%)	Silt (%)	Clay (%)	USDA Classification[a]
Cover CSL	CSL–205	20	59	21	Silt loam
	CSL–206[b]	16	58	26	Silt loam
	CSL–208	22	58	20	Silt loam
	Mean	19	58	22	Silt loam
	SEM[c]	2	0	2	
Soil Borrow Area	SBA–1	32	60	8	Silt loam
	SBA–2	40	44	15	Loam
	SBA–3	38	42	16	Loam
	SBA–4	34	69	3	Silt loam
	SBA–5	40	50	10	Silt loam
	SBA–6	32	63	2	Silt loam
	SBA–7	23	58	19	Silt loam
	SBA–8	38	46	16	Loam
	Mean	35	54	11	Silt loam
	SEM	2	3	2	

[a]USDA soil classification system.
[b]Sample pit was excavated adjacent to ports 206a and 206b.
[c]Standard error of the mean.

Table 3. Gravimetric Moisture Content, Dry-Weight Soil Bulk Density, Porosity, and Saturation for the Shiprock Cover CSL

Sample Number	Description	Moisture Content (wt. %)	Dry Bulk Density (g/cm^3)	Porosity[a] (%)	Water Content (vol. %)	Saturation (%)
205s	Sand drainage layer	2.48				
205csl	Bulk CSL sample	15.28				
205csl(v)	Volume sample of CSL	14.38	1.99	26.8	28.66	(107.3)
206s	Sand drainage layer	2.56				
206csl	Bulk CSL sample	13.32				
206csl(v)	Volume sample of CSL	14.32	1.90	30.1	27.23	90.5
208s	Sand drainage layer	2.41				
208csl	Bulk CSL sample	11.77				
208csl(v)	Volume sample of CSL	11.18	2.04	25.0	22.75	93.5
Mean			1.98	27.1	26.21	97.1
SEM[b]			0.04	1.66	1.78	5.16

[a]A mean particle density of 2.72 g/cm^3 from DOE (1989) was used to calculate porosity.
[b]Standard error of the mean.

Table 4. Soil Particle Size and Texture Classification for Windblown Dust Accumulating in Rock Layer

Sample Location	Sample Number	Sand (%)	Silt (%)	Clay (%)	USDA Classification[a]
Disposal Cell	RD-205	20	75	5	Silt loam
Cover	RD-206	25	66	9	Silt loam
	RD-208	28	65	7	Silt loam
	Mean	24.3	68.7	7.0	Silt loam
	SEM[b]	4.0	5.5	2.0	

[a]USDA soil classification system.
[b]Standard error of the mean.

Table 5. Summary of Analysis of Variance of Data From Hydroprobe Ports in Subsurface Soil at Shiprock Disposal Cell

Layer	Factor	ANOVA *F* Value[a]	*P* Value
Rock	Probe	$F_{3,168} = 1.08$	0.3604
Rock	Date	$F_{8,163} = 2.03$	0.0458
Rock	Depth	$F_{5,166} = 173.24$	0.0000
CSL	Probe	$F_{3,494} = 3.90$	0.0090
CSL	Date	$F_{8,489} = 6.38$	0.0000
CSL	Depth	$F_{17,480} = 4.45$	0.0000

[a]ANOVA = analysis of variance.

Table 6. Results of In Situ Saturated Hydraulic Conductivity Sampling on North Side Slope of Shiprock Disposal Cell Cover Using Air-Entry Permeameters

Site Description	Moisture Content (%)			Dry Bulk Density (g/cm^3)	Wet Bulk Density (g/cm^3)	Calculated Porosity (%)	Air-Filled Porosity (%)	Saturated Conductivity (cm/s)
	g/g (%)	cm^3/cm^3 (%)	Saturation (%)					
Tamarix (*no roots)*	14.8	27.1	87.4	1.83	2.10	31.0	3.9	$1.29\ \mathrm{H}\ 10^{-4}$
Tamarix (roots)	12.8	24.7	90.1	1.92	2.17	27.4	2.7	$4.76\ \mathrm{H}\ 10^{-8}$
Chrysothamnus (no roots)	12.3	22.4	71.6	1.82	2.05	31.3	8.9	$6.12\ \mathrm{H}\ 10^{-6}$
Chrysothamnus (roots)	12.2	22.7	75.7	1.86	2.08	30.0	7.2	$5.34\ \mathrm{H}\ 10^{-6}$
Salsola (no *roots)*	14.7	24.3	64.3	1.65	1.89	37.8	13.5	$1.19\ \mathrm{H}\ 10^{-4}$
Salsola (roots)	8.6	15.2	45.9	1.77	1.93	33.1	17.9	$5.12\ \mathrm{H}\ 10^{-6}$

Table 7. Summary of Physical and Hydraulic Properties of Tailings From the 1988 Study (DOE 1989)

Summary Statistics	**Moisture Content (%)**			**Dry Bulk Density (g/cm^3)**	**Particle Density (g/cm^3)**	**Calculated Porosity (%)**	**Saturated Conductivity (cm/s)**
	g/g (%)	**cm^3/cm^3 (%)**	**Saturation (%)**				
Mean	12.6	23.3	78.4	1.91	2.72	29.4	3.5 H 10^{-8}
SEM[a]	2.14	3.23	7.47	0.057	0.014	2.40	NA
Maximum	21.0	36.5	(108.6)	2.06	2.78	41.4	NA
Minimum	5.7	11.7	51.1	1.63	2.67	22.9	NA
n	8	8	8	8	9	8	1

[a]Standard error of the mean.

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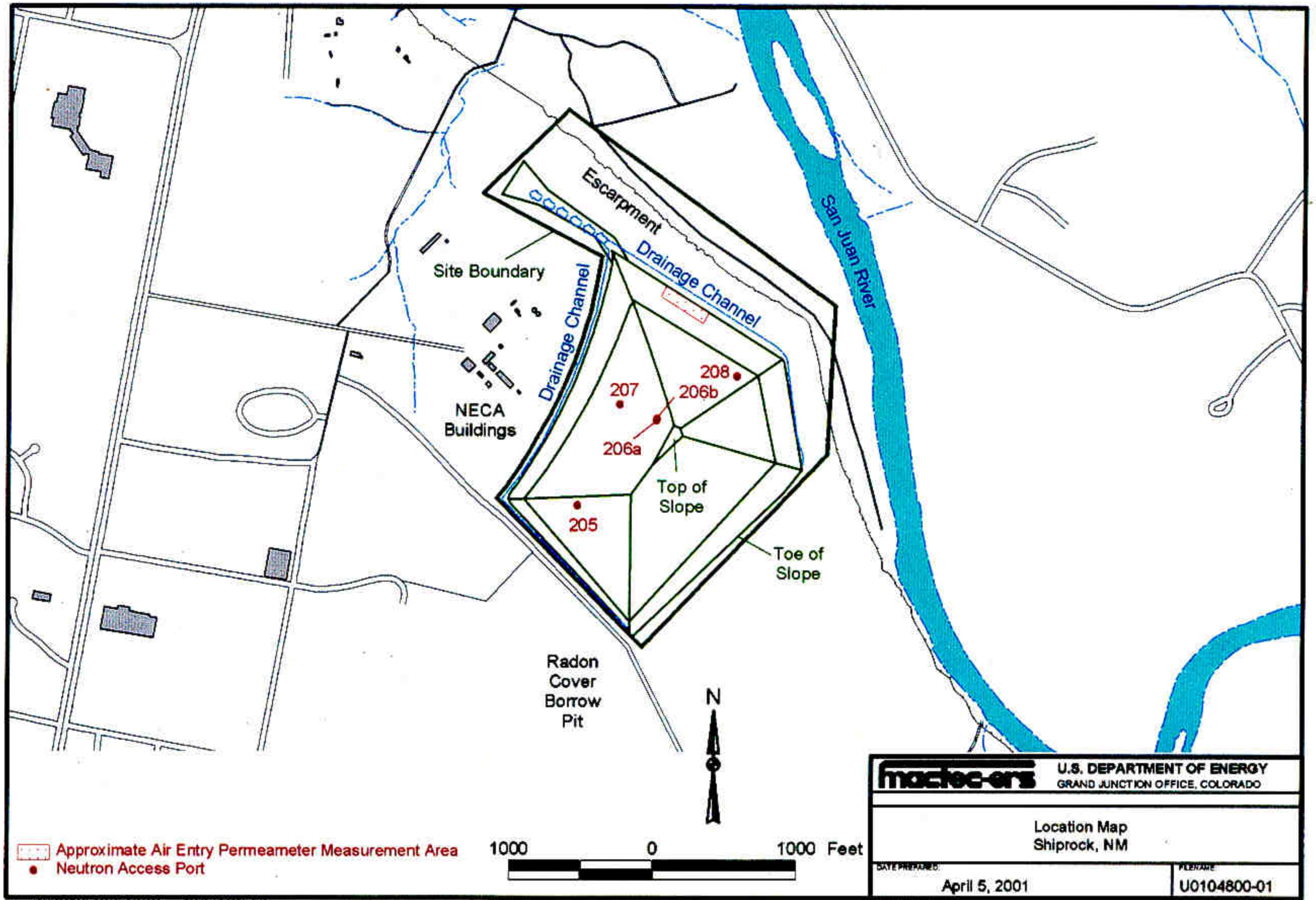

Figure 1. Sampling Locations

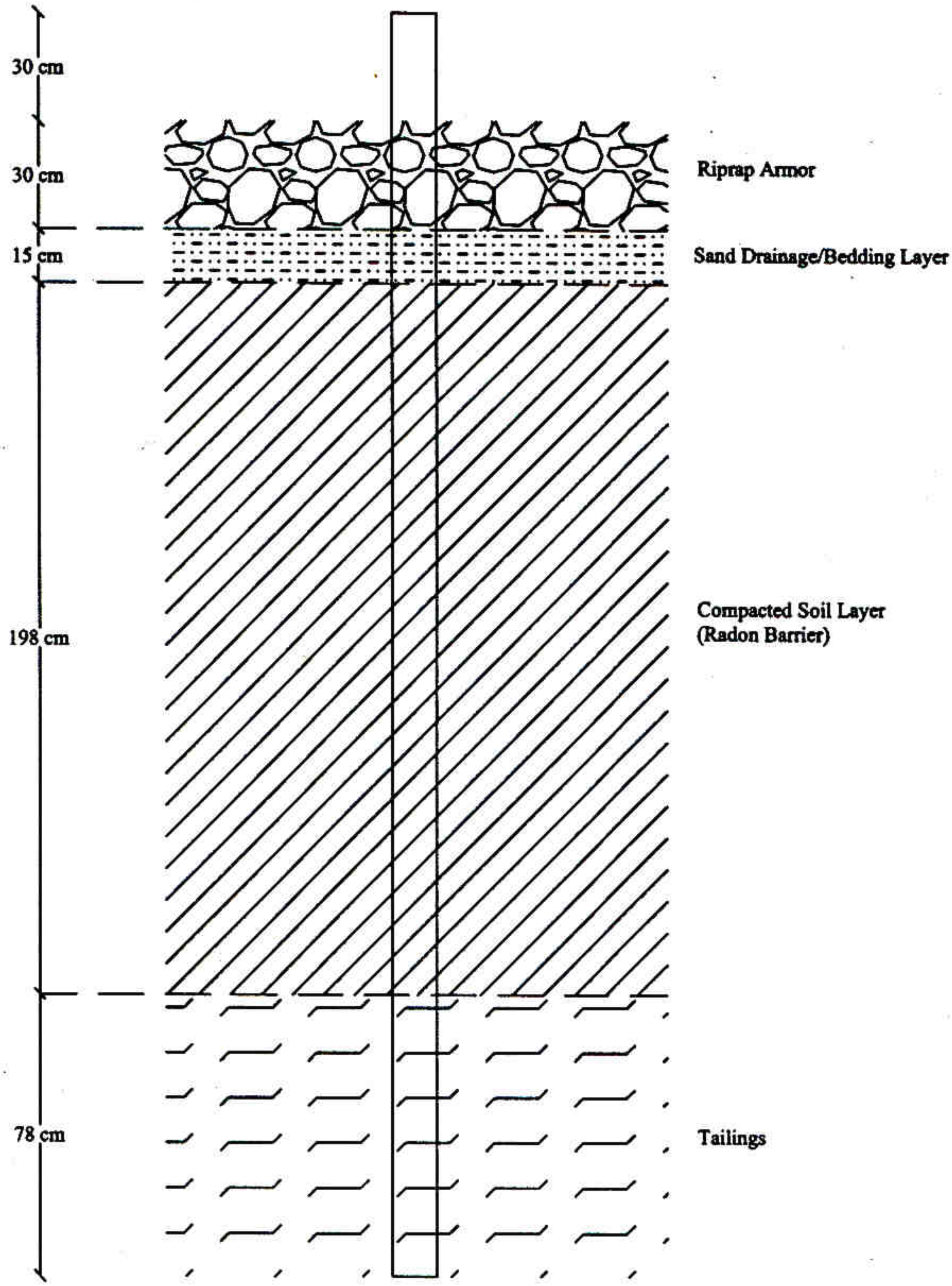

Figure 2. Neutron Hydroprobe Port Depths in the Shiprock Disposal Cell Cover

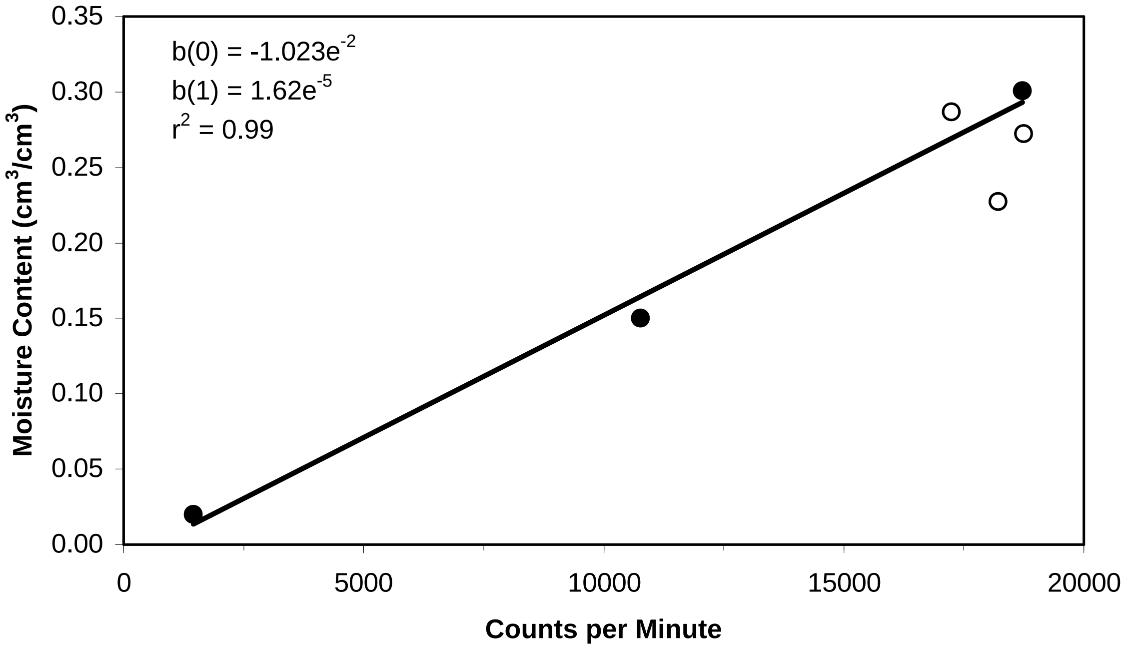

Figure 3. Calibration to Determine Volumetric Moisture Content in Shiprock CSL From Neutron Hydroprobe Data

Note: The calibration included data from barrel measurements only (closed circles). Open circles are results of field measurements.

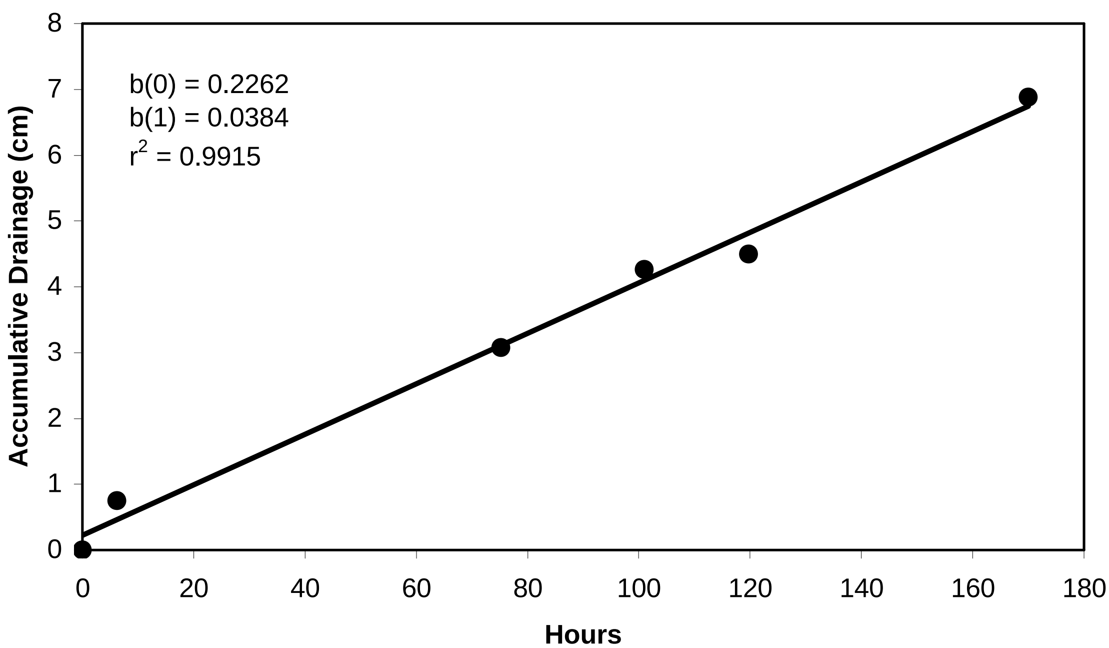

Figure 4. Infiltration of Water Into CSL Soil in a Barrel From Neutron Hydroprobe Data

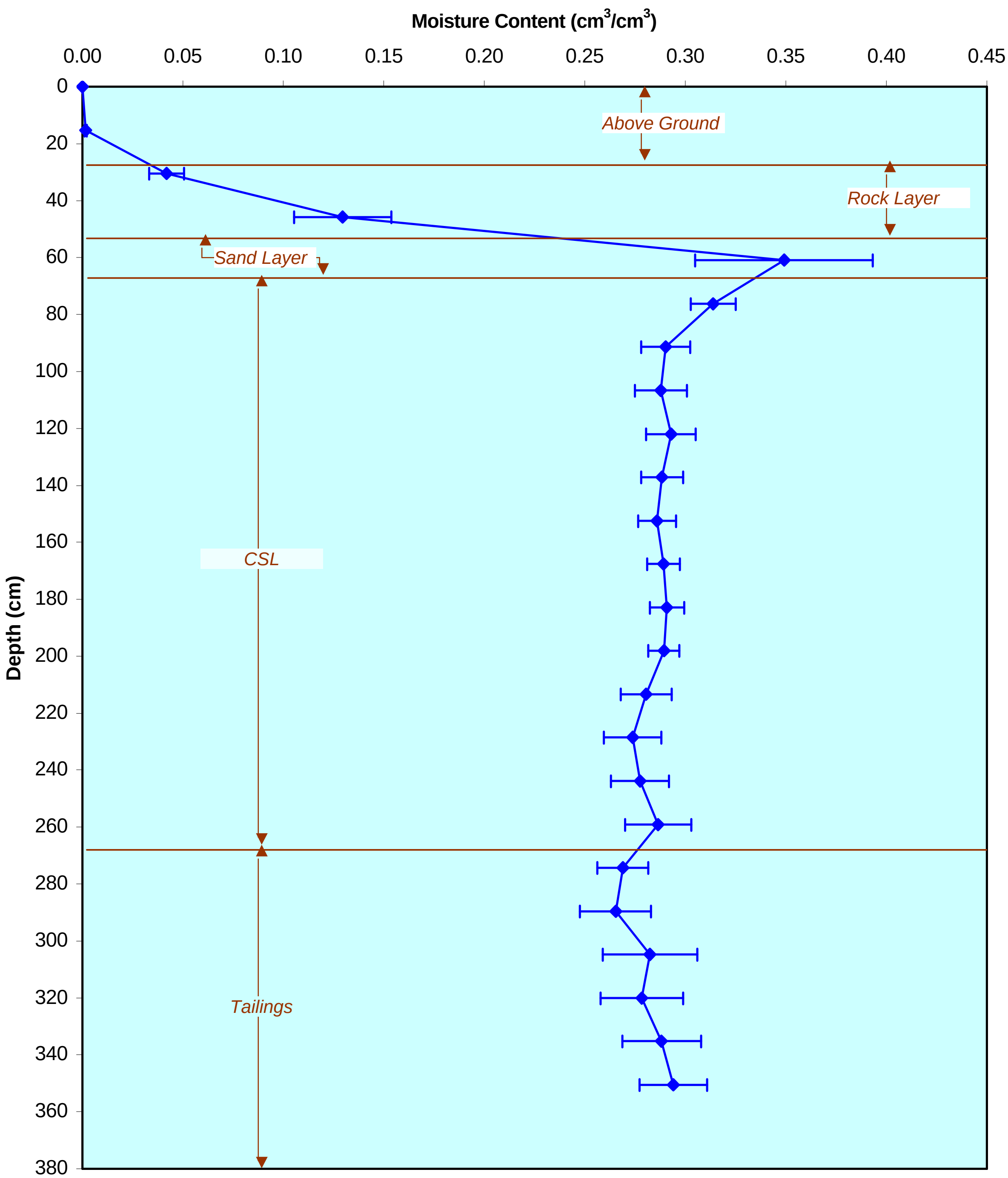

Figure 5. Profile of Volumetric Soil Moisture Content in Disposal Cell Cover and Upper Tailings Averaged for Data From all Probe Ports and Sampling Dates (error bars are 2 SEM)